中国生态农业学报 2016年2月 第24卷 第2期
Chinese Journal of Eco-Agriculture, Feb. 2016, 24(2): 131−141

DOI: 10.13930/j.cnki.cjea.150904

不同施氮量及种植密度对小麦开花期氮素积累转运的影响*

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摘 要 本文以小麦品种'周麦22'为材料，研究了不同施氮量[0 kg(N)·hm^{-2}、120 kg(N)·hm^{-2}、240 kg(N)·hm^{-2}和360 kg(N)·hm^{-2}，以N_0、N_1、N_2和N_3表示]和种植密度(225×10^{4}基本苗·hm^{-2}、375×10^{4}基本苗·hm^{-2}和525×10^{4}基本苗·hm^{-2}，以M_1、M_2和M_3表示)处理下小麦植株地上部不同空间分布各器官的氮素含量及其转运特性。结果表明：施氮量、种植密度及二者互作对开花期、成熟期植株地上部各器官氮素含量的影响均达显著水平。不同施氮量及种植密度处理小麦开花期至成熟期各营养器官氮含量和积累量下降。开花期和成熟期，植株单茎氮积累量为7.27~59.65 mg·茎$^{-1}$和8.48~60.83 mg·茎$^{-1}$，以N_0M_3处理最低，以N_3M_2最高。从空间位置看，植株地上部各营养器官开花期氮含量、氮积累量及花后氮转运量和对籽粒氮的贡献率均随空间位置下移而降低。营养器官氮含量、积累量及转运量随施氮量增加而呈递增趋势，上部和中部营养器官氮转运率高于50%。营养器官对籽粒氮的总贡献率高于67%。增施氮肥配套合理的种植密度，可以促进植株地上各营养器官氮的积累和转运，对植株下部器官氮积累转运的作用尤为明显，高肥及中密度处理(N_3M_2)下倒四叶、倒四节及余叶和余节氮含量和积累量增加，缩小了与上部各器官的差异。植株地上部群体氮素转运量为28.56~549.49 kg·hm^{-2}，亦随施氮量增加而增加，以穗部和茎节氮转运量较高。施氮量对籽粒产量、蛋白质含量及蛋白质产量影响显著。施氮量与种植密度互作对籽粒蛋白质含量及产量影响显著，种植密度对籽粒蛋白质产量的影响亦达显著水平。从氮素转运和产量性状来看，施用氮肥240 kg·hm^{-2}配套225×10^{4}基本苗·hm^{-2}的种植密度是黄淮小麦玉米两熟区小麦生产较为适宜的栽培模式。

关键词 小麦 氮肥 种植密度 氮素积累 地上部器官 空间分布 籽粒产量
中图分类号: S512.1; S311 **文献标识码:** A **文章编号:** 1671-3990(2016)02-0131-11

Effects of different nitrogen application amounts and seedling densities on nitrogen accumulation and transport in winter wheat at anthesis stage*

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Abstract To determine reasonable nitrogen (N) application amount and seedling density of wheat for improving N utilization efficiency and yield, N contents in organs in different parts of wheat plant were measured, and wheat response to N application (in terms of N accumulation and translocation) and planting density was studied. In the field experiment, 'Zhoumai 22' wheat cultivar was used in a split-plot design with N fertilization amount as the main plot and seedling density as the secondary plot. Nitrogen fertilization amounts during the whole growth period were 0 kg·hm^{-2} (N_0), 120 kg·hm^{-2} (N_1), 240 kg·hm^{-2} (N_2) and 360 kg·hm^{-2} (N_3), respectively, while seedling densities were 225×10^4 seedlings·hm^{-2} (M_1), 375×10^4 seedlings·hm^{-2} (M_2) and

* 国家自然科学基金项目(U1204313)和国家科技支撑计划项目(2011BAD16B14, 2012BAD14B08, 2013BAD07B14)资助
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收稿日期: 2015-08-12 接受日期: 2015-11-05

* Supported by the National Natural Science Foundation of China (U1204313) and the National Key Technology Support Program of China (2011BAD16B14, 2012BAD14B08, 2013BAD07B14)
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Received Aug. 12, 2015; accepted Nov. 5, 2015

525×10^4 seedlings·hm^{-2} (M_3), respectively. The results showed that N application amounts, seedling densities and the interactions of the two factors had significant effects on N contents in organs in different positions of aboveground wheat at anthesis and maturity stages. N content and accumulation in the vegetative organs of wheat at maturity declined compared with those at anthesis. Total N accumulation in individual plant was changed within range of 7.27–59.65 mg·stem^{-1} at anthesis and 8.48–60.83 mg·stem^{-1} at maturity, and the maximum data was observed in N_3M_2 treatment, while the minimum level was observed in N_0M_3 treatment. N content and accumulation in vegetative organs of wheat apparently decreased with decreasing of spatial position at anthesis stage. Also N transport and contribution rate of vegetative parts to grain had the same spatial distribution trend. It suggested that flag-leaf and the first upper internode were higher while the fourth upper leaf and the fourth upper internode as well as the other bottom parts near the ground were apparently lower. N content, accumulation and transport capacity of vegetative organs increased with increasing N application rate. N transport rate in the organs of upper and middle spatial position exceeded 50%, and total N contribution rate of vegetative organs to grain exceeded 67%. Increased N fertilizer amount combined with suitable planting density improved the capacity of N accumulation and translocation in aboveground system. Among all the vegetative organs, the ones nearest the ground (such as the fourth upper leaf and internode) were more obviously affected by N application and seedling density while N content and accumulation in those parts were significantly higher under higher N application and medium-level density, narrowing the differences with upper parts of the plant. Also N transport of plant population (28.56–549.49 kg·hm^{-2}) increased with increasing N application amount, especially for plant spike and internode. Grain yield, grain protein content and protein yield were significantly influenced by N application rate. While grain protein content and protein yield were significantly driven by applied N amount and N amount/seedling density interactions, protein yield was driven by seedling density. Considering N transport and grain yield, N application at 240 kg·hm^{-2} and seedling density at 225×10^4 plant·hm^{-2} were suitable for ‘Zhoumai 22’ in wheat/corn double cropping in Huanghuai region.
Keywords Wheat; Nitrogen application; Seedling density; Nitrogen accumulation; Organs in aboveground part; Spatial distribution; Yield

氮肥施用和种植密度是小麦高产栽培的主要调控措施[1]。氮素是植物体重要的营养元素，直接参与植株器官建成及多种生理生化过程。研究表明，小麦营养器官氮同化、积累及转运与籽粒的产量和品质密切相关[2–4]，小麦籽粒氮约有20%来自开花后植株同化，80%来自开花前叶片、茎秆及颖片等部位的花后转移[5–7]。优化氮肥管理可以促进小麦植株抽穗后干物质及氮素积累[8]，有利于氮向籽粒转运，从而提高产量和氮肥利用率[9]，并降低氮残留对环境的污染[10–11]。随种植密度的增加，花前小麦营养器官积累氮的转运量、转运率以及对籽粒的贡献率均有增加[12–13]。在小麦生产过程中，氮肥和密度之间存在互作效应，在适当降低氮肥用量的条件下，增加种植密度有利于小麦吸收深层土壤氮素，减少土壤氮素残留[14]，提高群体光合性能而获得高产[15]。目前关于不同栽培措施下小麦植株氮素积累的研究，多是从植株整个营养体或不同器官的水平进行，而植株各器官氮素的空间分布研究较少。蒿宝珍等[16]研究了华北地区限水灌溉条件下氮肥对冬小麦冠层叶片氮素空间分布的影响，认为适量施氮可以增加叶层间氮素垂直分布梯度，促进氮素在植株体内进行再分配。为探讨氮肥施用量与种植密度对小麦植株氮素空间积累转运的影响，本研究测定了不同氮肥和种植密度处理下小麦植株开花期和成熟期地上不同空间层次各器官的氮素含量，分析了植株氮素空间积累及转运特征，以期为合理施肥配套适宜种植密度实现小麦高产和资源高效提供理论指导。

1 材料与方法

1.1 试验材料与设计

以黄淮麦区近年来主栽品种‘周麦 22’为试验材料，于 2013—2014 年在中国农业科学院新乡综合试验基地(河南省新乡市新乡县七里营镇中曹村，35°09′N，113°45′E)进行田间试验。土质为潮土，0~20 cm 土壤有机质含量 15.76 g·kg^{-1}，全氮 0.76 g·kg^{-1}，碱解氮 65.74 mg·kg^{-1}，速效磷 8.70 mg·kg^{-1}，速效钾 165.86 mg·kg^{-1}，pH 8.7。

试验采用裂区设计，主区为氮肥，全生育期施氮量分别为 0 kg(N)·hm^{-2}、120 kg(N)·hm^{-2}、240 kg(N)·hm^{-2} 和 360 kg(N)·hm^{-2}(以 N_0、N_1、N_2 和 N_3 表示)，于播前、拔节期、开花期按比例(5∶3.5∶1.5)分次施入；副区为种植密度，分别为 225×10^4 基本苗·hm^{-2}、375×10^4 基本苗·hm^{-2} 和 525×10^4 基本苗·hm^{-2}(以 M_1、M_2 和 M_3 表示)。前茬夏玉米秸秆全部还田，底施 K_2O 90 kg·hm^{-2}、P_2O_5 240 kg·hm^{-2}。2013 年 10 月 11 日人工开沟播种，行距 20 cm。小区面积 19.2 m^2

(4.8 m × 4 m), 重复 3 次。2014 年 6 月 5 日成熟收获。

1.2　研究方法

在小麦开花期(4 月 23 日)和成熟期(6 月 5 日), 选取长势一致的单茎 20 个, 将叶片按空间分布层次分为旗叶、倒二叶、倒三叶、倒四叶和余叶, 茎鞘分为倒一节、倒二节、倒三节、倒四节和余节, 穗部分为穗轴+颖壳、籽粒。样品洗净烘至恒重, 称量其干物质质量, 粉碎后半微量凯氏定氮法测定全氮含量。

1.3　数据计算及分析

根据样品质量及全氮含量计算样品氮素积累量, 并计算各器官氮素转运量、转运率及对籽粒氮素的贡献率[17]。以 SPSS 13.0 进行数据分析, 其中多重比较采用 LSD 法, 小写字母表示 0.05 水平差异显著。

2　结果与分析

2.1　不同施氮量及种植密度下小麦开花期的地上部氮含量

小麦开花期, 不同施氮量及种植密度处理下植株地上部不同空间层次各器官氮含量为 1.94~52.51 $mg\cdot g^{-1}$, 以旗叶氮含量最高, 其次是倒二叶和倒三叶(表 1)。不同器官间氮含量表现为叶片>穗轴颖壳>茎鞘。从空间分布看, 叶片氮含量随叶位下降而降低, 表现为旗叶>倒二叶>倒三叶, 倒四叶和余叶较低; 茎鞘氮含量亦随位置下移而降低, 表现为倒一节>倒二节>倒三节, 以倒四节和余节氮含量最低。

方差分析结果表明, 氮肥用量、种植密度及二者互作对小麦植株开花期地上不同空间层次各器官氮含量的影响均达显著水平($P<0.05$), 以氮肥的影响作用更强。施肥处理(N_1、N_2 和 N_3)下, 各部位氮含量显著高于不施肥(N_0)处理($P<0.05$)。M_1 密度下, 穗轴+颖壳、旗叶、倒三叶、倒四叶、倒一节和倒二节氮含量表现为随施氮量增加呈“先升后降”趋势, 以 N_2 处理表现最高; 倒二叶、倒三节、倒四节、余节氮含量均随施氮量增加而升高, 余叶亦以 N_3 处理下氮含量最高。M_2 密度下, 余叶和倒二节氮含量以 N_3 处理最高, 其他器官氮含量均以 N_2 处理表现最高。M_3 密度下, 倒四叶、余叶、倒一节、倒二节、倒四节氮含量以 N_2 最高, 其他器官氮含量均随施氮量增加而增加, 以 N_3 处理表现最高。近地面的倒四叶、余叶及倒四节和余节, 其氮含量随施氮量增加尤为明显, 因此增施氮肥可有效提高下部叶片和茎鞘对氮素的吸收, 延缓其衰老死亡。

不施氮(N_0)处理下, 穗轴+颖壳、叶片(余叶除外)、倒三节氮含量以 M_1 最高, 余叶、倒二节、余节氮含量以 M_2 最高, 倒一节和倒四节氮含量则随种植密度的增加而升高, 以 M_3 处理表现最高。N_1 处理下, 倒四节氮含量以 M_1 最高, 穗轴+颖壳、倒二叶、倒三叶、余叶、倒二节、倒三节、倒四节氮含量以 M_2 处理最高, 旗叶、倒一节、余节氮含量则以 M_3 处理最高。N_2 处理下, 旗叶氮含量以 M_1 最高, 倒二节氮含量以 M_3 最高, 其他器官均以 M_2 表现最高。N_3 处理下, 穗轴+颖壳、旗叶、倒二叶、倒三叶、倒一节氮含量以 M_3 最高, 倒四叶、余叶、倒二节、倒三节、倒四节和余叶以 M_2 处理表现较高。近地面的倒四叶和余叶及倒四节和余节氮含量在施氮量 N_2 和 N_3 时以 M_2 最高, 与其他种植密度相比, 其与上部各器官氮含量差距缩小。

2.2　不同施氮量及种植密度处理下小麦成熟期的地上部氮含量

小麦成熟期, 不同施氮量及种植密度处理下植株地上部各器官氮含量为 1.69~28.26 $mg\cdot g^{-1}$, 籽粒氮含量最高(表 2)。不同器官间氮含量表现为籽粒>叶片>穗轴颖壳>茎节。从空间分布来看, 叶片氮含量在 N_0、N_1 和 N_2 处理下以倒四叶、余叶较高, 在 N_3 处理下以倒二叶和倒三叶较高, 茎节氮含量以余节表现最高(除 N_0M_2 处理外), 以倒二节、倒三节氮含量最低。

方差分析结果表明, 不同施氮量、种植密度及二者互作对成熟期植株地上部各器官氮含量的影响均达显著水平($P<0.05$), 其中旗叶和余叶氮含量的影响因素表现为施氮量>种植密度>施氮量×种植密度, 余节氮含量表现为施氮量×种植密度>种植密度>施氮量, 其余器官均表现为施氮量>施氮量×种植密度>种植密度。从不同施氮量处理来看, 成熟期地上部各器官氮含量随氮肥施用量增加而增加, 在 N_2、N_3 处理下达到较高值。种植密度主要影响冠层下部余叶、余节氮含量。N_0 处理下, 籽粒氮含量各种植密度间无显著差异, 穗轴+颖壳、旗叶、倒二叶、倒三叶及倒一节、倒二节氮含量表现为 $M_2>M_1>M_3$, 倒四叶、余叶、倒三节、倒四节和余节氮含量则在 M_1 处理下最高。N_1 处理下, 籽粒、旗叶、余叶氮含量表现为 M_1 和 M_2 显著高于 M_3, 穗轴+颖壳、倒二叶、倒三叶及倒四叶氮含量以 M_2 最高, 茎节氮含量均以 M_1 最高。N_2 处理下, 穗轴+颖壳、倒四叶、倒一节和倒二节氮含量以 M_1 处理最高, 其他各营养器官氮含量均以 M_2 处理最高。N_3 处理下, 籽粒、穗轴+颖壳、旗叶、倒二叶氮含量以 M_1 处理最高, 倒四叶和余叶以 M_2 处理最高, 茎节氮含量均以 M_1 最高。

2.3　不同施氮量及种植密度处理下小麦开花期和成熟期的地上部氮积累

开花至成熟期, 植株单茎氮总积累量增加, 而各营养器官氮积累量却有不同程度降低(表 3)。开花

表 1　不同施氮量和种植密度下小麦开花期植株地上部不同空间层次各器官氮含量

Table 1　N contents in aboveground organs at different positions of wheat plant at anthesis stage under different N application amount and seedling density treatments　mg·g^{-1}

部位 Organ	处理 Treatment											
	N_0			N_1			N_2			N_3		
	M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3
穗轴+颖壳 Glume and spike-stalk	16.87±0.04j	12.21±0.04l	14.41±0.09k	16.98±0.17i	22.83±0.03c	21.60±0.01e	19.08±0.01g	23.41±0.03a	22.60±0.03d	17.15±0.13h	21.07±0.03f	23.08±0.07b
旗叶 Flag leaf	32.42±0.09i	27.92±0.22j	27.97±0.08j	43.22±0.27h	43.43±0.14h	48.03±0.22e	49.95±0.00b	48.52±0.05d	49.48±0.18c	45.10±0.04g	46.69±0.07f	52.51±0.17a
倒二叶 The 2nd upper leaf	25.24±0.04j	22.45±0.06k	15.62±0.02l	40.58±0.27h	45.13±0.05e	38.85±0.00i	42.21±0.26g	49.75±0.07a	47.01±0.07c	42.70±0.09f	45.60±0.05d	48.69±0.32b
倒三叶 The 3rd upper leaf	18.27±0.08i	14.59±0.03k	15.79±0.10j	34.83±0.11g	36.82±0.39e	29.58±0.13h	38.24±0.11c	43.61±0.07a	35.41±0.24f	37.43±0.02d	38.41±0.10c	42.36±0.06b
倒四叶 The 4th upper leaf	8.60±0.01j	8.20±0.05k	6.27±0.00l	26.52±0.04f	12.81±0.04i	20.00±0.25g	30.05±0.03d	35.07±0.07a	32.80±0.29c	28.80±0.09e	33.56±0.09b	13.55±0.01h
余叶 Residue leaves	6.14±0.02k	6.84±0.01i	6.78±0.01j	13.35±0.01d	15.76±0.02a	7.83±0.07h	11.58±0.02f	15.28±0.02b	11.96±0.02e	13.97±0.06c	15.79±0.02a	10.71±0.04g
倒一节 The 1st upper internode	11.93±0.01k	12.59±0.01j	14.69±0.01i	19.95±0.03g	19.93±0.03g	20.50±0.17f	21.78±0.12c	22.92±0.09a	22.76±0.14b	18.60±0.05h	21.09±0.08e	21.55±0.08d
倒二节 The 2nd upper internode	6.41±0.01j	11.62±0.08g	6.41±0.00j	11.47±0.00h	15.58±0.09d	13.01±0.00f	15.36±0.01e	10.03±0.01i	19.94±0.00a	11.36±0.04h	19.28±0.14b	18.85±0.21c
倒三节 The 3rd upper internode	4.10±0.01i	3.89±0.01j	3.75±0.00k	5.95±0.01h	11.10±0.03f	8.53±0.02g	11.05±0.12f	21.32±0.16a	11.41±0.01e	15.82±0.00c	17.52±0.09b	13.17±0.03d
倒四节 The 4th upper internode	1.94±0.01k	3.89±0.01j	3.93±0.01j	5.96±0.01h	7.94±0.00g	4.44±0.01i	10.91±0.00e	18.59±0.20a	12.63±0.08b	12.04±0.09c	11.87±0.05d	8.64±0.01f
余节 Residue internodes	4.08±0.01i	4.20±0.01i	4.15±0.03i	6.12±0.03g	4.39±0.01h	7.83±0.06f	11.38±0.08c	18.88±0.24a	10.22±0.07e	10.87±0.02d	16.00±0.04b	10.89±0.01d

N_0、N_1、N_2、N_3 表示施氮量分别为 0 kg(N)·hm^{-2}、120 kg(N)·hm^{-2}、240 kg(N)·hm^{-2} 和 360 kg(N)·hm^{-2} 处理, M_1、M_2、M_3 表示种植密度分别为 225×10^4 基本苗·hm^{-2}、375×10^4 基本苗·hm^{-2} 和 525×10^4 基本苗·hm^{-2} 处理; 表中数值为平均数±标准差; 同行数据后不同小写字母表示处理间差异显著(P<0.05)。下同。N_0, N_1, N_2 and N_3 show nitrogen fertilizer amounts during the whole wheat growth stage of 0 kg(N)·hm^{-2}, 120 kg(N)·hm^{-2}, 240 kg(N)·hm^{-2} and 360 kg(N)·hm^{-2}, respectively. M_1, M_2 and M_3 showed the seedling densities of 225×10^4 seedlings·hm^{-2}, 375×10^4 seedlings·hm^{-2} and 525×10^4 seedlings·hm^{-2}, respectively. Data in the table are shown as mean ± standard deviation. Different small letters following data in the same row mean significant difference at 0.05 level among treatments. The same below.

表 2　不同施氮量和种植密度下小麦成熟期植株地上部不同空间层次各器官氮含量

Table 2　N contents in aboveground organs at different positions of wheat plant at mature stage under different N application amount and seedling density treatments　mg·g^{-1}

部位 Organ	处理 Treatment											
	N_0			N_1			N_2			N_3		
	M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3
籽粒 Grain	19.80±0.52d	19.91±0.23d	19.69±0.55d	21.74±0.49c	21.05±0.54c	19.34±0.04d	25.45±0.15b	25.53±0.80b	26.17±0.19b	28.26±0.10a	28.06±0.20a	27.55±0.78a
穗轴+颖壳 Glume and spike-stalk	5.30±0.00j	5.85±0.01i	3.27±0.01k	7.15±0.03e	8.80±0.04d	6.44±0.01h	9.71±0.05a	6.82±0.01g	8.93±0.06c	8.96±0.03c	9.12±0.01b	7.00±0.02f
旗叶 Flag leaf	6.78±0.01k	7.76±0.01j	6.10±0.01l	9.35±0.03f	8.62±0.06h	8.05±0.01i	10.30±0.01d	10.74±0.02c	10.03±0.01e	13.46±0.01a	12.61±0.08b	9.22±0.07g
倒二叶 The 2nd upper leaf	5.52±0.03k	6.18±0.04j	5.16±0.02l	8.21±0.02h	8.51±0.07g	7.72±0.05i	9.99±0.09d	10.29±0.06c	9.13±0.05f	14.80±0.21a	13.71±0.12b	9.64±0.01e
倒三叶 The 3rd upper leaf	6.12±0.02j	5.83±0.01k	6.11±0.01j	7.20±0.01h	7.40±0.01g	6.96±0.01i	10.61±0.02e	11.17±0.10d	9.85±0.01f	13.62±0.03c	14.07±0.08b	14.55±0.02a
倒四叶 The 4th upper leaf	8.39±0.01g	7.33±0.04h	6.79±0.03i	9.53±0.04f	12.37±0.08d	9.46±0.02f	12.41±0.03d	12.33±0.05d	11.22±0.01e	12.85±0.04c	13.79±0.14a	13.10±0.00b
余叶 Residue leaves	8.13±0.07f	8.00±0.05g	7.86±0.02g	12.08±0.01d	12.00±0.03d	10.40±0.01e	13.69±0.12b	13.75±0.02b	12.01±0.10d	13.00±0.03c	13.95±0.10a	12.90±0.25a
倒一节 The 1st upper internode	5.51±0.03h	6.54±0.04g	4.19±0.01k	6.67±0.01f	4.30±0.02j	5.42±0.01i	7.45±0.02c	6.50±0.01g	7.11±0.05d	8.93±0.05a	8.36±0.04b	6.85±0.07e
倒二节 The 2nd upper internode	3.04±0.01j	6.15±0.03c	2.91±0.02k	4.41±0.00g	3.78±0.00i	3.98±0.02h	6.16±0.01c	5.14±0.02e	4.67±0.02f	8.53±0.02a	6.61±0.01b	5.86±0.00d
倒三节 The 3rd upper internode	3.58±0.02h	2.52±0.00k	3.07±0.04i	3.76±0.00g	2.62±0.00j	1.69±0.02l	5.13±0.00f	6.58±0.02d	6.19±0.02e	7.81±0.02a	7.22±0.01b	6.97±0.05c
倒四节 The 4th upper internode	5.00±0.03g	2.90±0.00k	4.84±0.01i	5.78±0.01e	4.97±0.00h	4.47±0.00j	5.24±0.01f	5.86±0.02d	5.01±0.01g	8.52±0.04a	8.40±0.01b	7.15±0.01c
余节 Residue internodes	11.30±0.01a	5.40±0.03i	5.31±0.00j	7.57±0.02g	7.54±0.01g	7.35±0.04h	7.88±0.03f	8.21±0.02d	7.89±0.05f	9.89±0.00b	9.32±0.01c	8.10±0.04e

表 3　不同施氮量与种植密度下小麦植株个体开花期和成熟期地上部不同空间层次各器官氮积累量

Table 3　N accumulation amounts of aboveground organs at different positions of wheat plant at anthesis and mature stages under different N application amount and seedling density treatments

mg·stem^{-1}

生育期 Growth stage	部位 Organ	处理 Treatment											
		N_0			N_1			N_2			N_3		
		M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3
开花期 Anthesis stage	穗轴+颖壳 Glume and spike-stalk	2.67±0.01j	2.60±0.01j	1.47±0.01k	6.71±0.07g	12.50±0.02a	7.91±0.00f	6.38±0.00h	9.70±0.01c	8.76±0.01d	4.30±0.03i	8.33±0.01e	10.16±0.03b
	旗叶 Flag leaf	0.78±0.00j	0.74±0.01j	0.49±0.00k	2.68±0.02h	3.04±0.01g	2.38±0.01i	4.07±0.00d	4.59±0.00c	3.69±0.01e	3.27±0.00f	6.14±0.01a	5.25±0.02b
	倒二叶 The 2nd upper leaf	0.64±0.00j	0.71±0.00i	0.31±0.00k	3.65±0.02e	3.50±0.00g	1.79±0.00h	5.42±0.03a	3.58±0.01f	4.80±0.01c	3.99±0.01d	5.49±0.01a	5.09±0.03b
	倒三叶 The 3rd upper leaf	0.39±0.00j	0.47±0.00i	0.32±0.00k	2.37±0.01f	3.04±0.03d	1.72±0.01h	2.45±0.01e	3.03±0.01d	2.27±0.02g	3.07±0.00c	7.76±0.02a	3.88±0.01b
	倒四叶 The 4th upper leaf	0.15±0.00i	0.20±0.00h	0.10±0.00j	2.06±0.00d	2.43±0.01b	1.08±0.01g	1.37±0.00f	2.19±0.00c	2.05±0.02d	1.89±0.01e	5.76±0.01a	1.05±0.00g
	余叶 Residue leaves	0.22±0.00k	0.61±0.00i	0.52±0.00j	0.78±0.00g	2.37±0.00c	0.70±0.01h	1.16±0.00f	1.34±0.00e	1.15±0.00f	1.57±0.01d	4.16±0.00a	2.69±0.01b
	倒一节 The 1st upper internode	2.07±0.00k	2.57±0.00j	2.06±000k	7.95±0.01c	8.57±0.01a	5.95±0.05h	8.31±0.05b	5.76±0.02i	6.38±0.04f	6.05±0.02g	6.53±0.02e	6.80±0.03d
	倒二节 The 2nd upper internode	1.31±0.00j	2.51±0.02h	0.97±0.00k	5.11±0.00e	5.55±0.03c	3.44±0.00g	6.12±0.00a	2.37±0.00i	5.34±0.00d	3.66±0.01f	5.82±0.04b	5.08±0.06e
	倒三节 The 3rd upper internode	0.68±0.00j	0.82±0.00i	0.47±0.00k	0.81±0.00i	4.48±0.01b	2.12±0.00h	3.78±0.04d	4.32±0.03c	2.63±0.00g	3.76±0.00e	4.58±0.02a	3.18±0.01f
	倒四节 The 4th upper internode	0.17±0.00j	0.46±0.00i	0.45±0.00i	1.39±0.00e	2.90±0.00a	0.89±0.00h	2.41±0.00c	2.94±0.03a	2.11±0.01d	1.32±0.01f	2.59±0.01b	1.18±0.00g
	余节 Residue internodes	0.07±0.00l	0.63±0.00h	0.11±0.00k	0.22±0.00j	1.45±0.00f	0.91±0.01g	0.53±0.00i	2.72±0.03a	2.05±0.01c	1.94±0.00d	2.46±0.01b	1.67±0.00e
成熟期 Mature stage	籽粒 Grain	8.13±0.21i	10.48±0.12h	6.28±0.12j	33.25±0.75f	39.59±1.02b	26.79±0.06g	35.95±0.21d	34.85±1.09e	38.88±0.29b	34.65±0.12e	44.61±0.23a	37.85±1.08c
	穗轴+颖壳 Glume and spike-stalk	0.84±0.00j	1.24±0.00i	0.33±0.00k	2.82±0.01f	4.82±0.02a	2.36±0.00g	3.25±0.02d	2.83±0.00f	3.46±0.02c	2.25±0.01h	3.61±0.00b	3.08±0.01e
	旗叶 Flag leaf	0.11±0.00g	0.14±0.00g	0.06±0.00h	0.38±0.00e	0.32±0.00f	0.29±0.00f	0.42±0.00d	0.73±0.00b	0.55±0.00c	0.73±0.00b	0.86±0.01a	0.72±0.01b
	倒二叶 The 2nd upper leaf	0.10±0.00k	0.14±0.00j	0.07±0.00l	0.35±0.00g	0.33±0.00h	0.19±0.00i	0.37±0.00f	0.51±0.00d	0.39±0.00e	0.90±0.01b	1.01±0.01a	0.60±0.00c
	倒三叶 The 3rd upper leaf	0.09±0.00j	0.12±0.00i	0.08±0.00k	0.30±0.00g	0.30±0.00g	0.17±0.00h	0.47±0.00e	0.51±0.00d	0.44±0.00f	0.67±0.00c	0.91±0.01a	0.68±0.00b
	倒四叶 The 4th upper leaf	0.10±0.00k	0.13±0.00j	0.09±0.00l	0.33±0.00g	0.43±0.00f	0.26±0.00i	0.48±0.00e	0.56±0.00c	0.50±0.00d	0.30±0.00h	0.69±0.01b	0.71±0.00a
	余叶 Residue leaves	0.07±0.00j	0.22±0.00i	0.27±0.00h	0.82±0.00c	0.86±0.00b	0.65±0.00f	0.80±0.01d	0.82±0.00c	0.82±0.01c	0.62±0.00g	0.96±0.01a	0.73±0.01e
	倒一节 The 1st upper internode	0.87±0.00k	1.02±0.01j	0.42±0.00l	2.04±0.00e	1.34±0.01i	1.39±0.00h	2.12±0.01d	1.82±0.00g	2.14±0.01c	2.22±0.01b	2.43±0.01a	2.00±0.02f
	倒二节 The 2nd upper internode	0.34±0.00k	0.86±0.00i	0.21±0.00l	1.16±0.00e	0.93±0.00h	0.83±0.00j	1.53±0.00b	1.08±0.00f	1.06±0.00g	1.63±0.00a	1.50±0.00c	1.38±0.00d
	倒三节 The 3rd upper internode	0.29±0.00i	0.26±0.00j	0.15±0.00l	0.61±0.00g	0.47±0.00h	0.26±0.00k	0.80±0.00f	1.10±0.00c	1.08±0.00d	0.92±0.00e	1.24±0.00a	1.13±0.01b
	倒四节 The 4th upper internode	0.40±0.00j	0.22±0.00l	0.24±0.00k	0.78±0.00c	0.73±0.00e	0.55±0.00i	0.59±0.00h	0.77±0.00d	0.63±0.00g	0.66±0.00f	1.03±0.00a	0.89±0.00b
	余节 Residue internodes	0.19±0.00l	0.52±0.00j	0.28±0.00k	0.68±0.00h	1.44±0.00d	1.30±0.01f	0.95±0.00g	1.46±0.00c	1.39±0.01e	0.60±0.00i	1.98±0.00a	1.61±0.01b

期，植株氮积累量为 7.27~59.63 mg·茎$^{-1}$，以 N_0M_3 处理最低，N_3M_2 处理表现最高，其次是 N_1M_2。施氮处理下，植株个体开花期氮积累量均显著高于 N_0 处理。各器官氮积累量以穗轴+颖壳和倒一节较高，叶片和茎节氮积累量均随空间位置下移而降低。成熟期，植株个体氮积累量为 8.48~60.83 mg·茎$^{-1}$，仍以 N_0M_3 处理最低，以 N_3M_2 处理最高。各器官氮积累量以籽粒最高，籽粒氮积累量占植株地上部氮积累量的 68.30%~76.81%，其次是穗轴颖壳，其氮积累量占植株地上部的 3.94%~9.34%。倒一节至第四节氮积累量随空间位置下降而降低，余节氮积累量在施氮处理下高于上部各茎节，仅次于倒一节。成熟期叶片氮积累量在 N_0、N_1、N_2 处理下以余叶氮最高，N_3 处理下以倒四叶氮积累量最低。

将植株按空间层次分为上部(旗叶、倒一节、穗部)、中部(倒二叶、倒二节、倒三叶、倒三节)和下部(倒四叶、倒四节、余叶、余节)，施氮处理下空间各部氮素积累量显著高于 N_0 处理。开花期，上、中、下 3 部分氮积累比例分别为 40%~55%、30%~40%和 10%~20%，上部、下部氮积累量随种植密度的增加呈先升后降变化趋势，以 M_2 处理较高。成熟期，上、中、下 3 部分氮素积累比例分别为 80%~90%、5%~10%和 5%~10%，3 部分氮积累量随种植密度的增加呈先升后降变化趋势，随施氮量的增加呈上升趋势。下部氮积累比例在 M_1、M_2 处理下，以 N_3 较高；在 M_3 处理下，以 N_0 较高；中部和上部氮积累比例分别在 N_3 处理和 N_2 处理下最高。

2.4 不同施氮量及种植密度处理下小麦植株地上部氮素的转运

施氮量和种植密度可调控植株氮素的分配。开花期至成熟期，植株个体地上部各器官氮转运量随空间位置下移而降低(表 4)。叶片以旗叶、倒二叶氮转运量较高，茎节以倒一节氮转运量最高。近地面的余叶、余节及倒四节在无氮(N_0)、低氮(N_1)处理下，部分种植密度处理下表现出氮素输入积累，高氮处理下则均表现为氮的输出转运。由此可以看出，氮肥施用可以明显促进植株下部器官氮的转运。各器官氮转运量随施氮量增加呈先快后慢增加趋势，施肥处理(N_1、N_2 和 N_3)显著高于 N_0 处理(P<0.05)。从不同种植密度来看，植株个体各器官氮转运量在 N_0、N_0、N_2 处理下以 M_1 最高，在高氮(N_3)处理下以 M_2 密度最高。

从植株各器官氮转运率(表 5)来看，上部、中部各器官氮转运率均高于 50%，施氮促进了器官氮素的转运。随施氮量的增加，下部各器官氮转运率增加，表现为下部倒四叶、倒四节及余叶积累氮的向外运转。

种植密度不同，表现为植株群体数的不同，植株群体氮转运量与植株个体氮转运量变化趋势亦不完全相同。植株群体地上部氮转运量为 28.59~549.39 kg·hm^{-2}(表 6)。从群体来看，氮转运量以穗轴+颖壳、倒一节、倒二节表现较高，且茎节>叶片。随施用氮肥的增加，群体氮转运量亦增加，在 N_0、N_1 处理下，群体氮转运量表现为 M_2 密度处理显著高于 M_3、M_1 处理；在 N_2、N_3 处理下，群体氮转运量表现为 M_1 密度处理显著低于 M_2、M_3 处理。各器官中，余节在 N_0M_1、N_0M_3、N_1M_1、N_1M_3、N_2M_1 处理下以及倒四节在 N_0M_1 处理下仍表现为氮的积累，在其他处理下表现为氮向其他器官进行运转；而其他器官均表现为氮的转运。

植株地上各器官氮素贡献率为 0.02%~26.10%，以穗轴颖壳、倒一节表现较高(表 7)。植株地上部对籽粒氮总的贡献率高于 67%，以 N_3M_2 最高，其次是 N_1M_2，施肥处理高于 N_0 处理。各器官对籽粒氮的贡献率亦表现为随空间位置的下降而降低。穗轴颖壳、倒一节对籽粒氮素贡献率随施氮量增加而减小，以 N_1 处理表现最高；叶片(余叶除外)对籽粒氮素贡献率随施氮量增加而增加，施肥处理(N_1、N_2 和 N_3)显著高于不施肥处理(N_0, P<0.05)。余节、倒四节氮素贡献率以 N_2 处理较高，而倒二节则以 N_0 处理较高，其余各部位均以 N_3 处理最高。就种植密度而言，各部位氮素转运对籽粒贡献率在 N_0 处理下以 M_3 最高，在施肥(N_1、N_2 和 N_3)处理下以 M_2 最高。

2.5 不同施氮量及种植密度处理小麦籽粒产量

氮肥施用对籽粒产量的影响达显著水平(P<0.05)，而种植密度及施氮量×种植密度的互作对籽粒产量影响未达显著水平。N_0、N_1、N_2 处理下，籽粒产量随施氮量呈递增变化趋势，N_3 处理略有下降，施肥(N_1、N_2、N_3)处理籽粒产量较 N_0M_1 高 3.54~5.44 倍，以 N_2M_1 最高。施氮量及施氮量×种植密度对籽粒蛋白质含量的影响达显著水平，其影响强度表现为施氮量>施氮量×种植密度>种植密度。施氮量、种植密度及二者互作对籽粒蛋白质产量的影响均达显著水平(P<0.05)，各因素影响强度表现为施氮量>种植密度>施氮量×种植密度。施氮(N_3、N_2 与 N_1)处理下，籽粒蛋白质含量及蛋白质产量显著高于不施肥(N_0)处理，且在 N_1、N_2 处理范围内随施氮量增加表现增加趋势，N_3 处理下，籽粒蛋白质含量持续增加，而蛋白质产量降低。N_0 处理下，蛋白质产量各种植密度间无显著差异，施肥(N_1、N_2 和 N_3)处理下蛋白质产量均以低种植密度(M_1)下最高(表 8)。

表 4　不同施氮量与种植密度下小麦植株地上部不同空间层次各器官氮转运量

Table 4　N transportation amounts of aboveground organs at different positions of wheat plant under different N application amount and seedling density treatments　mg·stem^{-1}

部位 Organ	处理 Treatment											
	N_0			N_1			N_2			N_3		
	M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3
穗轴+颖壳 Glume and Spike-stalk	1.83±0.01j	1.35±0.01k	1.14±0.01l	3.88±0.08g	7.69±0.04a	5.55±0.00d	3.13±0.02h	6.88±0.01c	5.30±0.01e	2.06±0.03i	4.72±0.02f	7.07±0.04b
旗叶 Flag leaf	0.67±0.00h	0.60±0.01hi	0.43±0.00i	2.30±0.02g	2.72±0.01e	2.09±0.01g	3.65±0.00c	3.85±0.01c	3.13±0.01d	2.54±0.00f	5.28±0.00a	4.53±0.01b
倒二叶 The 2nd upper leaf	0.55±0.00i	0.57±0.00i	0.25±0.00j	3.30±0.02d	3.17±0.01e	1.59±0.00h	5.05±0.03a	3.07±0.01g	4.40±0.01c	3.09±0.01f	4.48±0.00b	4.49±0.03b
倒三叶 The 3rd upper leaf	0.31±0.00k	0.35±0.00j	0.24±0.00l	2.07±0.01f	2.74±0.03c	1.55±0.01i	1.98±0.01g	2.52±0.00d	1.82±0.02h	2.39±0.00e	6.84±0.03a	3.19±0.00b
倒四叶 The 4th upper leaf	0.05±0.00k	0.07±0.00j	0.01±0.00l	1.73±0.00c	2.01±0.00b	0.82±0.01h	0.88±0.00g	1.64±0.00d	1.55±0.02f	1.59±0.00e	5.07±0.01a	0.34±0.00i
余叶 Residue leaves	0.16±0.00j	0.39±0.00f	0.24±0.00i	—	1.51±0.01c	0.06±0.01h	0.36±0.01g	0.53±0.00e	0.34±0.00h	0.95±0.00d	3.21±0.00a	1.97±0.03b
倒一节 The 1st upper internode	1.21±0.00l	1.55±0.00k	1.64±0.00j	5.91±0.01c	7.23±0.01a	4.57±0.05e	6.19±0.04b	3.95±0.03h	4.25±0.02f	3.84±0.03i	4.10±0.01g	4.80±0.01d
倒二节 The 2nd upper internode	0.97±0.00i	1.65±0.01g	0.76±0.00j	3.96±0.00c	4.63±0.03a	2.61±0.00e	4.59±0.00a	1.28±0.00h	4.28±0.00b	2.03±0.02f	4.32±0.04b	3.70±0.06d
倒三节 The 3rd upper internode	0.39±0.00j	0.56±0.00i	0.33±0.00k	0.20±0.00l	4.02±0.01a	1.85±0.00g	2.98±0.04d	3.22±0.03c	1.55±0.00h	2.84±0.00e	3.34±0.02b	2.05±0.01f
倒四节 The 4th upper internode	—	0.25±0.00j	0.21±0.00k	0.60±0.00g	2.17±0.00a	0.34±0.00h	1.81±0.00c	2.17±0.03b	1.49±0.01e	0.67±0.01f	1.56±0.01d	0.28±0.00i
余节 Residue internodes	—	0.11±0.00e	—	—	0.01±0.01g	—	—	1.26±0.03b	0.66±0.02c	1.34±0.00a	0.49±0.00d	0.06±0.01f

表 5　不同施氮量与种植密度下小麦植株地上部不同空间层次各器官氮转运率

Table 5　N transportation rates of aboveground organs at different positions of wheat plant under different N application amount and seedling density treatments　%

部位 Organ	处理 Treatment											
	N_0			N_1			N_2			N_3		
	M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3
穗轴+颖壳 Glume and Spike-stalk	68.59±0.07e	52.07±0.15j	77.27±0.06a	57.89±0.58h	61.48±0.24f	70.17±0.03c	49.10±0.31k	70.88±0.05b	60.47±0.19g	47.77±0.22l	56.69±0.10i	69.66±0.19d
旗叶 Flag leaf	86.05±0.03f	80.59±0.17j	86.91±0.03d	85.70±0.14g	89.51±0.04b	87.98±0.04c	89.75±0.01a	84.07±0.04i	85.04±0.05h	77.77±0.04k	86.03±0.07f	86.30±0.06e
倒二叶 The 2nd upper leaf	84.98±0.07g	80.32±0.16i	78.52±0.10j	90.44±0.04c	90.63±0.09c	89.20±0.07d	93.09±0.02a	85.64±0.10f	91.81±0.06b	77.39±0.28k	81.54±0.15h	88.25±0.08e
倒三叶 The 3rd upper leaf	78.19±0.04h	75.02±0.07k	75.82±0.11j	87.38±0.03c	90.25±0.12a	90.26±0.05a	80.92±0.02f	83.04±0.12d	80.44±0.15g	78.03±0.04i	88.21±0.10b	82.35±0.00e
倒四叶 The 4th upper leaf	35.94±0.15h	36.19±0.03h	11.98±0.36j	84.00±0.05c	82.46±0.06d	75.47±0.25e	64.61±0.12g	74.68±0.04f	75.37±0.24e	84.33±0.01b	88.02±0.09a	32.00±0.03i
余叶 Residue leaves	69.16±0.14c	64.31±0.13d	46.65±0.25g	—	63.60±0.14e	7.91±0.96k	30.87±0.50i	39.15±0.02h	29.21±0.43j	60.32±0.06f	77.04±0.14a	72.95±0.63b
倒一节 The 1st upper internode	58.28±0.20k	60.27±0.20j	79.73±0.07b	74.35±0.08d	84.41±0.06a	76.73±0.23c	74.50±0.08d	68.46±0.18f	66.55±0.01g	63.34±0.30h	62.80±0.04i	70.58±0.17e
倒二节 The 2nd upper internode	74.23±0.07g	65.67±0.09i	78.36±0.16c	77.32±0.01d	83.34±0.09a	75.85±0.09e	75.01±0.02f	54.21±0.16k	80.08±0.07b	55.35±0.27j	74.17±0.15g	72.85±0.30h
倒三节 The 3rd upper internode	57.30±0.41k	68.42±0.05h	68.93±0.46g	25.05±0.10l	89.57±0.02a	87.56±0.13b	78.78±0.22c	74.48±0.11e	59.04±0.09j	75.43±0.06d	72.97±0.09f	64.41±0.31i
倒四节 The 4th upper internode	—	53.23±0.03f	46.29±0.22h	43.45±0.18i	74.75±0.02b	38.43±0.08j	75.37±0.05a	73.76±0.38c	70.28±0.18d	50.46±0.12g	60.32±0.19e	24.14±0.03k
余节 Residue internodes	—	17.24±0.53e	—	—	0.62±0.38g	—	—	46.38±0.57b	32.04±0.92c	69.16±0.05a	19.80±0.08d	3.83±0.55f

表 6 不同施氮量与种植密度下小麦植株群体地上部不同空间层次各器官氮转运量

Table 6 N transportation amounts of aboveground organs at different positions of plant of wheat population under different N application amount and seedling density treatments kg·hm^{-2}

部位 Organ	处理 Treatment											
	N_0			N_1			N_2			N_3		
	M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3
穗轴+颖壳 Glume and Spike-stalk	8.55±0.03k	11.03±0.05j	8.55±0.06k	27.79±0.49h	61.68±0.25e	45.10±0.01f	32.16±0.20g	78.47±0.15b	68.26±0.04c	25.40±0.29i	66.45±0.16d	96.32±0.42a
旗叶 Flag leaf	3.10±0.01k	3.79±0.03j	3.03±0.01k	15.41±0.12i	19.79±0.06g	16.43±0.08h	36.08±0.00e	42.61±0.06c	36.36±0.15d	29.20±0.04f	62.80±0.06a	56.39±0.16b
倒二叶 The 2nd upper leaf	2.54±0.00k	3.62±0.01j	1.83±0.00l	22.00±0.15h	22.99±0.04g	12.50±0.01i	49.77±0.30d	33.80±0.08f	50.04±0.10c	35.50±0.04e	54.30±0.01b	55.40±0.40a
倒三叶 The 3rd upper leaf	1.43±0.01k	2.31±0.01i	1.82±0.01j	13.85±0.05g	19.90±0.23f	12.12±0.06h	19.66±0.06f	27.88±0.01c	21.48±0.18e	27.49±0.00d	80.66±0.27a	40.47±0.06b
倒四叶 The 4th upper leaf	0.26±0.00j	0.76±0.00i	0.33±0.00j	11.62±0.01e	14.88±0.03d	6.55±0.10h	8.89±0.02f	18.48±0.03b	18.55±0.21b	18.10±0.05c	59.74±0.11a	6.97±0.01g
余叶 Residue leaves	0.72±0.00k	2.80±0.00h	2.38±0.01i	0.40±0.00l	11.99±0.04c	1.04±0.06j	3.85±0.05g	6.97±0.00e	5.95±0.03f	11.27±0.05d	39.68±0.00a	26.23±0.24b
倒一节 The 1st upper internode	5.66±0.02j	11.56±0.00i	12.15±0.01h	40.50±0.09f	53.33±0.05d	36.62±0.39g	61.72±0.41b	45.33±0.27e	53.03±0.31d	45.25±0.30e	55.13±0.19c	64.94±0.16a
倒二节 The 2nd upper internode	4.52±0.01l	11.72±0.09j	5.71±0.00k	26.93±0.01f	34.23±0.22e	20.95±0.02h	45.77±0.04d	15.53±0.02i	50.48±0.03b	24.39±0.19g	54.27±0.47a	49.41±0.68c
倒三节 The 3rd upper internode	1.82±0.02k	3.89±0.01i	2.60±0.01j	1.82±0.01k	29.21±0.09e	14.56±0.01h	29.63±0.41d	36.33±0.32b	20.19±0.00g	32.73±0.02c	42.28±0.26a	28.90±0.13f
倒四节 The 4th upper internode	—	1.99±0.00i	2.05±0.01i	4.59±0.02g	16.50±0.01d	3.16±0.01h	18.07±0.01c	24.52±0.37a	18.23±0.15c	8.17±0.08e	21.41±0.13b	7.13±0.01f
余节 Residue internodes	—	2.00±0.01f	—	—	2.19±0.04f	—	—	15.89±0.35a	11.06±0.24d	15.64±0.04b	12.67±0.05c	7.55±0.07e

表 7 不同施氮量与种植密度下小麦植株地上部不同空间层次各器官对籽粒氮素的贡献率

Table 7 N contribution ratios of aboveground organs at different positions to grain of wheat plant under different N application amount and seedling density treatments %

部位 Organ	处理 Treatment											
	N_0			N_1			N_2			N_3		
	M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3	M_1	M_2	M_3
穗轴+颖壳 Glume and Spike-stalk	22.58±0.51a	12.89±0.23f	18.09±0.54e	11.69±0.49g	19.43±0.60c	20.71±0.04b	8.71±0.11i	19.75±0.66c	13.62±0.12f	5.93±0.09j	10.59±0.17h	18.70±0.64d
旗叶 Flag leaf	8.24±0.19d	5.69±0.12h	6.77±0.24g	6.91±0.21g	6.88±0.20g	7.81±0.06e	10.16±0.06c	11.07±0.36b	8.06±0.03de	7.34±0.01f	11.84±0.15a	11.98±0.37a
倒二叶 The 2nd upper leaf	6.73±0.18h	5.42±0.09j	3.91±0.15k	9.94±0.29d	8.01±0.19g	5.95±0.01i	14.04±0.00a	8.81±0.30f	11.32±0.11c	8.92±0.05e	10.04±0.10d	11.87±0.25b
倒三叶 The 3rd upper leaf	3.78±0.12i	3.34±0.05j	3.81±0.11i	6.23±0.16f	6.93±0.26d	5.78±0.04g	5.51±0.05g	7.23±0.23c	4.69±0.01h	6.91±0.02e	15.34±0.09a	8.44±0.25b
倒四叶 The 4th upper leaf	0.67±0.01h	0.69±0.01h	0.19±0.00i	5.20±0.12b	5.07±0.12b	3.04±0.04e	2.46±0.01f	4.70±0.15c	3.97±0.02d	4.59±0.00c	11.36±0.16a	0.89±0.03g
余叶 Residue leaves	1.91±0.05e	3.71±0.04c	3.83±0.19c	—	3.81±0.11c	0.21±0.03h	0.99±0.02g	1.51±0.05f	0.87±0.00g	2.74±0.02d	7.18±0.09a	5.20±0.21b
倒一节 The 1st upper internode	14.88±0.35d	14.76±0.21d	26.10±1.12a	17.79±0.36b	18.28±0.48b	17.06±0.15c	17.22±0.01c	11.33±0.43f	10.93±0.02g	11.07±0.12f	9.19±0.06h	12.68±0.34e
倒二节 The 2nd upper internode	11.95±0.28d	15.72±0.31a	12.16±0.47c	11.90±0.26d	11.70±0.22d	9.74±0.03f	12.77±0.09b	3.68±0.12h	11.01±0.09e	5.84±0.07g	9.68±0.25f	9.78±0.13f
倒三节 The 3rd upper internode	4.80±0.07h	5.34±0.05g	5.20±0.26	0.61±0.01j	10.15±0.29a	6.91±0.01f	8.29±0.07c	9.24±0.37b	4.00±0.03i	8.19±0.04d	7.50±0.16e	5.41±0.19g
倒四节 The 4th upper internode	—	2.36±0.03g	3.29±0.10f	1.81±0.03h	5.49±0.14b	1.28±0.00i	5.04±0.03c	6.22±0.29a	3.82±0.01d	1.93±0.03h	3.51±0.00e	0.75±0.02j
余节 Residue internodes	—	1.04±0.02e	—	—	0.02±0.01g	—	—	3.62±0.2b	1.69±0.05c	3.87±0.00a	1.09±0.02d	0.17±0.03f

表 8　不同施氮量与种植密度下小麦籽粒产量和蛋白质含量
Table 8　Grain yields and protein contents of wheat under different N application amount and seedling density treatments

处理 Treatment		籽粒产量 Grain yield (kg·hm^{-2})	蛋白质含量 Protein content (%)	蛋白质产量 Protein yield (kg·hm^{-2})
N_0	M_1	1 780±150d	11.54±0.43d	205±7.57i
	M_2	1 770±240d	11.61±0.19d	205±3.35i
	M_3	1 790±140d	11.48±0.45d	205±8.12i
N_1	M_1	8 525±605bc	12.68±0.40c	1 081±34.5f
	M_2	8 415±495c	12.27±0.45c	1 033±37.47g
	M_3	8 088±1242c	11.28±0.03d	912±2.72h
N_2	M_1	11 472±775a	14.84±0.12b	1 702±14.2a
	M_2	9 355±525bc	14.88±0.66b	1 392±61.64d
	M_3	9 855±1908b	15.26±0.16b	1 503±15.79c
N_3	M_1	9 905±625b	16.48±0.08a	1 632±8.07b
	M_2	8 822±492bc	15.06±0.16b	1 328±14.39e
	M_3	9 430±950bc	16.06±0.65a	1 515±60.90c

同列数据后不同小写字母表示 0.05 水平下差异显著。Different small letters following data in the same column mean significant difference at 0.05 probability level.

3　讨论与结论

小麦生育后期营养器官氮素有效再分配对调控氮养分有显著效应[18]。本研究中, 开花期与成熟期小麦植株地上各层次器官氮含量分别为 1.94~52.51 mg·g^{-1}和 1.69~28.26 mg·g^{-1}, 植株个体氮积累量分别为 7.27~59.63 mg·茎$^{-1}$和 8.45~60.83 mg·茎$^{-1}$。植株个体氮素含量和积累量在开花期以叶片最高, 成熟期以籽粒最高。成熟期营养器官氮含量和积累量较开花期降低, 植株个体氮积累量和群体氮积累量则高于开花期, 与已有研究[19−20]结果一致。从空间位置看, 开花期叶片及茎节氮含量和积累量均表现为随空间位置下移而降低。成熟期, 由于器官氮的转运, 各器官氮的空间分布与开花期不一致, 茎鞘氮含量以余节最高, 叶片氮含量在无氮(N_0)、低氮(N_1)、中氮(N_2)处理下以余叶和倒四叶较高, 而在高氮(N_3)处理下以倒三叶和倒二叶表现较高。

蒿宝珍等[16]研究认为, 适量施氮(180~210 kg·hm^{-2})促进了华北地区冬小麦冠层叶片氮素有序转运, 提高了叶片氮素转运量、转运率和对籽粒贡献率。本研究中, 开花期和成熟期叶片、茎鞘及穗轴颖壳氮含量和积累量均表现为施肥处理(N_1、N_2 和 N_3)显著高于不施肥(N_0)处理, 且随施氮量的增加而增加, 近地面叶片(倒四叶和余叶)与茎鞘(倒四节和余节)及籽粒随施氮量增加更明显, 由此可知, 增施氮肥能显著提高营养器官和籽粒氮含量和积累量, 促进下部的叶片和茎节积累氮素, 有利于延缓衰老。有研究表明, 高种植密度促进植株群体氮积累量增加, 但花后氮转移却在种植密度较低时占有优势[21]。本研究中, 种植密度对植株地上部氮含量和积累量的影响主要在冠层下部, 倒四叶、余叶及倒四节和余节氮积累量均在 M_2 密度时最大, 缩小了与冠层上部各器官氮积累的差距, 植株整体氮的分配更合理。

植株籽粒、叶、茎等器官氮的积累、分配及转运协调配合才能保证其正常生长。花后营养器官具有较高氮转运量和适宜氮运转率才能防止生育后期时由于缺氮而造成叶片提前衰老死亡, 而营养体所积累的氮并不能过量转运至籽粒, 超负荷利用叶片及茎鞘氮会导致叶片早衰, 光合能力下降, 最终影响产量和氮素利用率[22]。本研究表明, 营养器官氮转运量及转运贡献率表现为叶片>茎节, 且叶片和茎节对籽粒氮的贡献率表现为随空间位置下降而降低。各营养器官氮转运量随施氮量增加呈先快速增加后缓慢增加趋势, 对籽粒总贡献率高于67%。不同施肥条件下种植密度对氮转运量和转运贡献率的影响不一致, 氮转运量在N_0、N_1、N_2施肥范围内以M_1最佳, 在N_3施肥下以M_2密度最佳; 转运贡献率在不施肥N_0下以M_3最高, 施肥(N_1、N_2和N_3)下以M_2最高。方差分析结果表明, 施氮量和种植密度共同调控植株氮分配及转运, 种植密度的效应低于施氮量, 但二者的互作效应不容忽视。

本研究是在黄淮麦玉两熟区前茬夏玉米秸秆还田的基础上进行的, 氮肥施用及种植密度对小麦植株地上部各层次器官氮的积累转运及籽粒产量性状均具有调控作用。植株地上部各器官氮积累及转运随空间位置的下移而降低, 施用氮肥配套适宜的种植密度可以促进植株地上部各器官对氮素的积累, 对植株下部器官氮积累和转运的作用尤为明显。从氮积累

转运及籽粒产量性状来看，施用氮肥240 kg·hm^{-2}配套种植密度为225×10^{4} 基本苗·hm^{-2}的配合模式，是该区较为合理的种植模式。

参考文献 References

[1] 于振文. 作物栽培学各论(北方本)[M]. 第2版. 北京: 中国农业出版社, 2013
Yu Z W. Monograph of Crop Cultivation (For the North)[M]. 2nd ed. Beijing: China Agriculture Press, 2013

[2] Pask A J D, Sylvester-Bradley R, Jamieson P D, et al. Quantifying how winter wheat crops accumulate and use nitrogen reserves during growth[J]. Field Crops Research, 2012, 126: 104–118

[3] Shewry P R. Improving the protein content and composition of cereal grain[J]. Journal of Cereal Science, 2007, 46(3): 239–250

[4] Basso B, Cammarano D, Fiorentino C, et al. Wheat yield response to spatially variable nitrogen fertilizer in Mediterranean environment[J]. European Journal of Agronomy, 2013, 51: 65–70

[5] Wang H, McCaig T N, DePauw R M, et al. Physiological characteristics of recent Canada western red spring wheat cultivars: Components of grain nitrogen yield[J]. Canadian Journal of Plant Science, 2003, 83(4): 699–707

[6] Xu Z Z, Yu Z W, Wang D, et al. Nitrogen accumulation and translocation for winter wheat under different irrigation regimes[J]. Journal of Agronomy and Crop Science, 2005, 191(6): 439–449

[7] 王德梅, 于振文, 张永丽, 等. 不同灌水处理条件下不同小麦品种氮素积累、分配与转移的差异[J]. 植物营养与肥料学报, 2010, 16(5): 1041–1048
Wang D M, Yu Z W, Zhang Y L, et al. Changes in nitrogen accumulation, distribution, translocation and nitrogen use efficiency in different wheat cultivars under different irrigation conditions[J]. Plant Nutrition and Fertilizer Science, 2010, 16(5): 1041–1048

[8] Li L P, Liu Y Y, Luo S G, et al. Effects of nitrogen management on the yield of winter wheat in cold area of northeastern China[J]. Journal of Integrative Agriculture, 2012, 11(6): 1020–1025

[9] 柴彦君, 熊又升, 黄丽, 等. 施氮对不同品种冬小麦氮素累积和运转的影响[J]. 西北植物学报, 2010, 30(10): 2040–2046
Chai Y J, Xiong Y S, Huang L, et al. Effects of nitrogen application on nitrogen accumulation, distribution and translocation of different winter wheat varieties[J]. Acta Botanica Boreali-Occidentalia Sinica, 2010, 30(10): 2040–2046

[10] 吴中伟, 樊高琼, 王秀芳, 等. 不同氮肥用量及其生育期分配比例对四川丘陵区带状种植小麦氮素利用的影响[J]. 植物营养与肥料学报, 2014, 20(6): 1338–1348
Wu Z W, Fan G Q, Wang X F, et al. Effects of nitrogen fertilizer levels and application stages on nitrogen utilization of strip-relay-intercropping wheat in Sichuan Hilly Areas[J]. Journal of Plant Nutrition and Fertilizer, 2014, 20(6): 1338–1348

[11] Ju X T, Xing G X, Chen X P, et al. Reducing environmental risk by improving N management in intensive Chinese agricultural systems[J]. Proceedings of the National Academy of Sciences of the United States of America, 2009, 106(9): 3041–3046

[12] Gooding M J, Pinyosinwat A, Ellis R H. Responses of wheat grain yield and quality to seed rate[J]. The Journal of Agricultural Science, 2002, 138(3): 317–331

[13] 王树丽, 贺明荣, 代兴龙, 等. 种植密度对冬小麦氮素吸收利用和分配的影响[J]. 中国生态农业学报, 2012, 20(10): 1276–1281
Wang S L, He M R, Dai X L, et al. Effect of planting density on nitrogen uptake, utilization and distribution in winter wheat[J]. Chinese Journal of Eco-Agriculture, 2012, 20(10): 1276–1281

[14] 张娟, 武同华, 代兴龙, 等. 种植密度和施氮水平对小麦吸收利用土壤氮素的影响[J]. 应用生态学报, 2015, 26(6): 1727–1734
Zhang J, Wu T H, Dai X L, et al. Effect of plant density and nitrogen level on nitrogen uptake and utilization of winter wheat[J]. Chinese Journal of Applied Ecology, 2015, 26(6): 1227–1734

[15] 曹倩, 贺明荣, 代兴龙, 等. 密度、氮肥互作对小麦产量及氮素利用效率的影响[J]. 植物营养与肥料学报, 2011,17(4): 815–822
Cao Q, He M R, Dai X L, et al. Effects of interaction between density and nitrogen on grain in yield and nitrogen use efficiency of winter wheat[J]. Plant Nutrition and Fertilizer Science, 2011, 17(4): 815–822

[16] 蒿宝珍, 姜丽娜, 方保停, 等. 限水灌溉冬小麦冠层氮分布与转运特征及其对供氮的响应[J]. 生态学报, 2011, 31(17): 4941–4951
Hao B Z, Jiang L N, Fang B T, et al. Effect of different nitrogen supply on the temporal and spatial distribution and remobilization of canopy nitrogen in winter wheat under limited irrigation condition[J]. Acta Ecologica Sinica, 2011, 31(17): 4941–4951

[17] 姜丽娜, 张凯, 宋飞, 等. 拔节期追氮对冬小麦产量、效益及氮素吸收和利用的影响[J]. 麦类作物学报, 2013, 33(4): 716–721
Jiang L N, Zhang K, Song F, et al. Effects of nitrogen topdressing at jointing stage on grain yield, benefit, absorption and utilization of nitrogen in winter wheat[J]. Journal of Triticeae Crops, 2013, 33(4): 716–721

[18] Basso B, Cammarano D, Troccoli A, et al. Long-term wheat response to nitrogen in a rainfed Mediterranean environment: Field data and simulation analysis[J]. European Journal of Agronomy, 2010, 33(2): 132–138

[19] 蔡瑞国, 李亚华, 张敏, 等. 雨养与灌溉条件下施氮对小麦

花后氮素累积与转运的影响[J]. 麦类作物学报, 2014, 34(3): 351–357
Cai R G, Li Y H, Zhang M, et al. Effects of nitrogen fertilizer rates on nitrogen accumulation and translocation after anthesis in wheat under rain-fed and irrigated conditions[J]. Journal of Triticeae Crops, 2014, 34(3): 351–357

[20] 邵云, 李万昌, 冯荣成, 等. 小麦–玉米轮作区西农 979 不同器官氮素转运及对籽粒贡献率的影响[J]. 麦类作物学报, 2011, 31(2): 265–269
Shao Y, Li W C, Feng R C, et al. Nitrogen translocation and conversion rate to grain of Xinong 979 in wheat-corn rotation area[J]. Journal of Triticeae Crops, 2011, 31(2): 265–269

[21] 查菲娜, 宋晓, 马冬云, 等. 种植密度对不同穗型冬小麦氮素积累和分配及子粒蛋白质含量的影响[J]. 河南农业大学学报, 2010, 44(1): 19–23
Zha F N, Song X, Ma D Y, et al. Study on the effect of planting density on the accumulation, distribution of nitrogen and grain protein in winter wheat of two spike types[J]. Journal of Henan Agricultural University, 2010, 44(1): 19–23

[22] Osaki M, Shinano T, Tadano T. Redistribution of carbon and nitrogen compounds from the shoot to the harvesting organs during maturation in field crops[J]. Soil Science and Plant Nutrition, 1991, 37(1): 117–128